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Cosmic Ray Origin, Acceleration and Propagation

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Abstract. This paper summarizes highlights of the OG3.1, 3.2 and 3.3 sessions of the XXVIth International Cosmic Ray Conference in Salt Lake City, which were devoted to issues of origin/composition, acceleration and propagation.

INTRODUCTION

A review of a collection of papers on cosmic ray origin, acceleration and propagation is necessarily broad. Historically, International Cosmic Ray Conferences have separated the papers in these extensive subjects for consideration by different Rapporteurs. However, since the Rome conference in 1995, a new precedent has been established with a review of all these fields becoming the responsibility of one individual. This has perhaps been propelled by the burgeoning number of astrophysics-related contributions to the meetings, and has reduced the comprehensiveness possible in a Rapporteur's written summary. This tract represents my attempt to assemble a description of interesting and new results presented at the Salt Lake City conference pertaining to the origin, acceleration and propagation themes. Space limitations preclude completeness, and accordingly I ask for forbearance from authors who feel their work is not given a sufficient exposure here. I also offer the standard disclaimer: that the views expressed here are personal, and may not reflect the perspective of "The Management," i.e. the contributing authors whose research has provided such a rewarding experience for this Rapporteur.

The material I was asked to report upon can be grouped into five categories: origin and composition, for which there were ≈ 11 papers, propagation of ions and electrons (26 papers), acceleration theory and astrophysical applications of acceleration models (33 papers), and discussions of ultra-high energy cosmic rays (UHECRs, 12 papers), with about 5 papers falling into the miscellaneous pot. These themes define the structure of this review, and there have been varying degrees of advancement in these fields. The citation scheme

adopted here identifies conference papers by OG 3.*.* designations, for which the reader should refer to the proceedings volumes, either hardcopy or on-line at <http://krusty.physics.utah.edu/~icrc1999/proceedings.html>.

ORIGIN AND COMPOSITION

The power supply for the acceleration of galactic cosmic rays is traditionally attributed to supernova remnants, yet there is much debate as to the mass and type of the progenitor stars, the specific nature of the circumstellar environment, and the galactic origin of the material accelerated. This discussion has spawned a field rich with ideas, with diagnostics largely provided by cosmic ray primary compositional data. The papers presented at this meeting generally relate to one of two problems: (i) the discussion of whether fresh supernova ejecta or environmental dust grains provide the seeds for cosmic ray acceleration, and (ii) explanations of the Li, Be, and B abundances, the well-known LiBeB problem.

Early ideas on cosmic rays focused on the environment for their acceleration, assuming some pre-existing seed population, rather than addressing the question of the origin of such seed material. Over a period of time, it became clear that the galactic cosmic ray (GCR)/solar photosphere abundance ratios provided valuable clues to the origin of galactic cosmic ray matter. Such ratios exhibit (e.g. see Silberberg, Tsao & Barghouty OG 3.1.06) a general enrichment of refractory elements (i.e. those with high condensation temperatures: Mg, Al, Si, Fe and Ni) relative to highly volatile ones (principally H, He, N, Ne and Ar). Two competing interpretations of this property emerged. The first is that low energy ions are pre-accelerated in stellar coronae to enrich the interstellar medium (ISM) before participating in acceleration at proximate SNR shells. In early work, [1,2] suggested that enrichment correlates with elemental first ionization potential (FIP; see also Silberberg, et al. OG 3.1.06), with high-FIP elements being somewhat suppressed. The FIP interpretation was largely driven by the discovery that FIP biases the composition of solar energetic particles; hence the connection to stellar coronae was made. The second proposal originated with Bibring & Cesarsky [3] and Epstein [4], where erosion products of grains formed from old material seed the acceleration process, so that enrichment should correlate with volatility [5]. The acceleration process is then naturally enhanced in non-linear SNR shocks with increasing mass-to-charge (A/Q) ratio of the species [6] in a manner commensurate with observed abundances.

While FIP proponents are invoking atomic physics concepts and a volatility interpretation appeals to molecular physics, the two views are not entirely opposite: FIP and volatility are clearly related quantities, albeit in a rather subtle manner. For many light and heavier sub-Fe elements, these two scenarios provide comparable GCR/solar abundance ratios. Yet success of the FIP-based models is contingent upon a number of disconnected and controversial assumptions, pertaining mostly to H, He, and ^{22}Ne and the contribution of Wolf-Rayet winds. In contrast, the volatility description offers a more coherent picture with fewer debatable assumptions,

depending principally on the chemistry and composition of interstellar grains. It is therefore becoming the more widely-accepted description, with the work of Lingenfelter & Ramaty (OG 3.1.05) coming out in support of volatility as the descriptor of cosmic ray abundances. Nevertheless, their research group had previously advocated [7] fresh supernova ejecta as the seeds for acceleration, as opposed to the grains created from older matter in the model of Meyer, Drury & Ellison [5,6]. This was a major point of controversy that was addressed and resolved at the Conference, based on two discriminating pieces of information.

The first diagnostic concerned the C and O ratios. These elements provide critical diagnostics since they possess intermediate FIPs and are moderately volatile, and hence are bridge elements between the volatiles and the refractories. Both are key products of nucleosynthesis in massive O and B stars, which are the progenitors of the type Ib and II supernova that dominate the observed supernova population. The property crucial to the success of the grain-acceleration proposition is that these two species are present in grains (e.g. various oxides and graphite) in just the appropriate amounts to explain their abundances [5]. Consequently, it becomes apparent that interstellar grain chemistry is the important parameter for the composition problem, and should be a focus of future research efforts.

The second decisive indicator concerned the age of the seeds for acceleration. Since grains can be much older than the SNRs that tap them, the grain-induced cosmic ray composition picture [5,6] is less subject to temporal restrictions provided by unstable nuclei that offer markers of the chronology of nucleosynthesis. Foremost among these is the electron K-capture decay of ^{59}Ni to ^{59}Co , with a half-life of around 10^5 years, for which the ACE experiment has recently provided discriminating information: the low abundance of ^{59}Ni relative to Fe and the high abundance of ^{59}Co (Weidenbeck et al., OG 1.1.01) implies a passing of at least 10^5 years between nucleosynthesis and acceleration. Meyer, Drury & Ellison have consistently argued that grains are easily old enough to satisfy the ACE temporal constraints. While Lingenfelter et al. [7] had advocated a fresh ejecta scenario, Higdon, Lingenfelter & Ramaty's contribution (OG 3.1.04) indicated an evolution in their position so that the two groups concurred that the ACE dataset does indeed provide age lower bounds that render fresh (i.e. young) ejecta unlikely seeds for the acceleration process at SNR shocks. Focus has now turned to timescales of ejecta mixing well in excess of 10^6 years, which can be suitably probed (Waddington, OG 3.2.33) by abundance measurements of actinides such as Th, Np, Cm and Pu. Westphal (OG 3.1.09) discussed the potential for the ECCO experiment aboard the International Space Station to provide such discriminating data.

The mixing question is pertinent to the discussion of whether superbubbles with many SNIb/SNII explosions as opposed to more isolated ISM regions with SNIa progenitors are the locales for cosmic ray origin. The site issue, still unresolved, provides a natural progression to the LiBeB problem. This longstanding conundrum relates to the abundances of Li, Be and B in old halo stars, the principal spallation products of reactions of nucleosynthetic or ambient ^{12}C , ^{14}N and ^{16}O in collisions with hydrogen and helium of either ISM or ejecta origin (see, e.g. Korejwo et al.

OG 3.2.22, for accelerator data on ^{12}C fragmentation/spallation cross-sections for various products in the GeV/nucleon range). Balmer-like line (Be II) observations indicate a linear correlation (e.g. Ramaty, Lingenfelter & Kozlovsky, OG 3.1.03; Fields & Olive OG 3.2.04) of the abundance of LiBeB with Fe metallicity (Fe/H) in these metal-poor stars (note that Fe/H is effectively an age parameter for these systems). Yet, theoretically (see the review in [8]) LiBeB is expected to increase quadratically with Fe/H, since, for a constant supernova rate, LiBeB/H should scale as the integral over time of the supernova rate times the total number of antecedent supernovae in the galaxy. This apparent conflict becomes cleaner, observationally, by considering Be alone, since it provides no ambiguities; some of the ^7Li is probably a product of primordial nucleosynthesis, and much of the ^{11}B population may result from neutrino-induced spallation (on ^{12}C) in supernovae.

Presentations on explaining Be/H evolution at the Conference included papers by Ramaty, Lingenfelter & Kozlovsky (OG 3.1.03) and Parizot & Drury (OG 3.1.18, OG 3.2.51). A result common to these two groups is that, by separating the light and metallic spallation participants in space, a decoupling between the metallicity of stars and their age is effected. This is achieved if there is no significant mixing between metal-poor ISM that is accelerated at a supernova remnant's forward shock and the enriched, high-metallicity ejecta accelerated at a remnant's reverse shock (Parizot & Drury OG 3.1.18). The dominant contributions to Be production are then spawned by (i) low metallicity ISM ions accelerated by forward shocks colliding with metal-rich supernova ejecta, and (ii) enriched ejecta material accelerated at reverse shocks interacting with light elements from the surrounding ISM. In each case, the Be production is independent of the ISM metallicity, generating a Be/H halo star abundance proportional to Fe/H metallicity. For this reason, Ramaty, Lingenfelter & Kozlovsky (OG 3.1.03) argue that the Be/H evolution with Fe/H is a strong indication that fresh ejecta are crucial to cosmic ray origin. Reconciling the Be production with the ACE observations of ^{59}Ni should be a major objective of future studies. Supernova/cosmic ray energetics also play a constraining role in this discussion, with both Ramaty, et al. and Parizot & Drury observing that there is an underproduction of Be (by over an order of magnitude) in the early galaxy if most supernovae explode in the average ISM. This has motivated papers by Higdon, Ramaty & Lingenfelter (OG 3.1.04) and Parizot & Drury (OG 3.2.51) that describe how a superbubble/starburst locale for LiBeB generation can provide prepared metallicity-enhanced environs due to the OB stellar associations. The production rate can increase more than tenfold to match the observed abundances in this scenario because the spallation reactions involving enriched ambient CNO can tap the greater accelerating potential of forward shocks in SNRs.

A cautionary note for the LiBeB problem was sounded by Fields and Olive (OG 3.2.04). While historically Fe/H has been used as the marker of metallicity for discussing Be production, Fields and Olive argued that the O/H ratio is a far more appropriate indicator since oxygen is an actual participant in the spallation reactions that spawn Be. The consequences of such a shift in perspective are substantial. The evolution of O/H does not trace Fe/H linearly so that O and Fe are different

indicators of metallicity. Accordingly, Fields and Olive observe that Be/H is more strongly dependent on O/H than Fe/H in halo (population II) star atmospheres, more closely resembling the quadratic dependence that was anticipated in incipient theoretical considerations of the LiBeB abundances. The implication of their work is that the so-called LiBeB problem is a “tempest in a teapot.” This is not entirely discouraging for theorists in their quest for nailing the origin of cosmic rays, since the data spread in the Be/H versus O/H diagram is considerable; observationally, it is more problematic to determine oxygen metallicity than Fe/H. Future refined observations from uniform/consistent stellar atmospheres should resolve this issue.

PROPAGATION

Studies of propagation have perhaps had the slowest evolution of the sub-fields covered here. This is essentially imposed by the pace at which new and discriminating experimental data relating to this complex problem are forthcoming. Properties of the interstellar medium of the galaxy remain enigmatic, presently prohibiting the elimination of any one of the handful of preferred propagation models. Foremost in this group is the “canonical” Leaky-Box approximation, the “tool of choice” for most members of the propagation community, due to its simplicity. More sophisticated and physically realistic models with various mutations are the halo diffusion picture, wind scenarios, turbulent diffusion model, and calculations invoking re-acceleration, each with their proponents (see [9] for a review). There are a number of standard tests for the viability of each of these; we shall explore here the latest results separately for the cases of propagation of ions and electrons.

Ions

A significant number of papers were presented, many producing very similar results. The leaky box model (LBM), where a “one-zone” scenario is envisaged with an escape length or rather grammage X_{lb} forming the principal model parameter, and the halo diffusion picture (HDM), where the galactic disk and halo represent two regions distinct in their source and diffusion properties, were the most common invocations (e.g. OG 3.1.16, 3.2.02, 3.2.03, 3.2.06, 3.2.07, 3.2.08, 3.2.09, 3.2.18, 3.2.32). While these two models dominate the discussion here, propagation in galactic winds (OG 3.1.16, 3.2.07, 3.2.13, 3.2.19, 3.2.32) and contributions from re-acceleration (OG 3.2.02, 3.2.07, 3.2.18, 3.2.32) were also considered.

In the LBM, the grammage parameter is often specified as a broken-power-law in rigidity R (e.g. Ptuskin et al. OG 3.2.02), increasing as a moderate power of particle velocity β at non-relativistic speeds and declining roughly as $X_{\text{lb}} \propto R^{-0.6}$ for relativistic energies E . This form is chosen (i) to explain the observed steepening of the primary cosmic ray spectrum from the approximately $E^{-2.1}$ spectrum expected at sources, (ii) match the observed secondary/primary ratios of stable species, and (iii) to accommodate spectral shapes observed in the transition region

between the modulated and unmodulated ion spectrum. Coefficients of these proportionalities are of the order of a few g/cm^2 to match densities of the interstellar medium and establish scale-heights above the galactic plane of the order of a kpc or so. Physically, the decline in X_{lb} as a function of rigidity corresponds to the expectation of greater losses for more energetic particles. The cosmic ray production in the LBM is homogeneous in space, not being coupled to the galactic plane.

The halo diffusion model (e.g. [10]) introduces more complexity, distinguishing between galactic disk and halo with different source densities and propagation characteristics in each region. Spatial uniformity can be assumed in each region (e.g. Ptuskin et al., OG 3.2.02, OG 3.2.32) or disk and halo can possess inhomogeneous distributions in altitude z above the plane (e.g. Strong & Moskalenko, OG 3.2.18). The diffusive escape parameter is usually set to $X_e \propto 1/\mathcal{D} \propto R^{-1/3}$ in accord with the dependence of the diffusion coefficient \mathcal{D} for Kolmogorov turbulence. Essentially, free escape arises at the halo extremities in this scenario, and the selective confinement of matter near the plane renders the pathlength distribution for losses exponential as in the Leaky Box model. The vertical height of the disk is constrained by the diffusive lengthscale $\sqrt{\mathcal{D}\tau}$ for “interesting” radioactive isotopes of ballistic lifetime τ (i.e. $\sim 10^6$ years; discussed below). A distinct advantage of the HDM is that it can accommodate the observed low cosmic ray anisotropies that are almost constant out to 10^{14} eV (e.g. [11]; see also Hillas OG 3.2.10) more easily than the LBM, due to its weaker dependence of loss scale on rigidity.

Primary source spectra for species such as carbon and iron alone are insufficient to discriminate between Leaky Box and halo diffusion models (e.g. see Ptuskin et al. OG 3.2.32), being more dependent on solar modulation properties (such as the assumed force-field potential: e.g. Webber, OG 3.2.8, Strong & Moskalenko OG 3.2.18). Stable secondary to primary ratios are somewhat more sensitive to model characteristics since they probe energy loss rates in matter traversal, i.e. X_{lb} and X_e , for different species involved in nuclear interactions with the interstellar medium. The most popular choices for these ratios, corresponding to spallation reactions involving the principal components of cosmic rays, are those of boron to carbon, B/C, and sub-iron group to iron nuclei, (Sc+Ti+V)/Fe. The spectrum of the spallation products traces that of the parent nuclei when they are created, with a subsequent steepening being induced by the energy-dependent propagation effects. Nevertheless, the increased data spread appearing in such ratios is sufficient to preclude unequivocal discrimination between models, so that the LBM and HDM are equally viable (e.g. OG 3.2.32) based on analysis of stable secondaries.

Hence considerable effort was expended in a number of papers that focused on radioactive isotopes. The abundances of suitable secondary radioactive nuclei provide clues to the confinement time of cosmic rays in the galaxy (e.g. Streitmatter & Stephens OG 3.2.03), and therefore offer observational diagnostics complementary to those engendered by matter traversal. Suitability is naturally governed by significant elemental abundances and lifetimes that approximate typical galactic disk diffusion timescales of 1 Myr. Therefore, excellent choices include ^{10}Be (beta decay, 2.3 Myr), ^{26}Al (inverse beta decay/ K-capture, 1.6 Myr) and ^{36}Cl (beta de-

cay, 0.4 Myr); ^{54}Mn is also a possible option, though its β^+ decay lifetime is still not precisely determined. While often-quoted Al/Mg and Cl/Ar fractions represent parent/daughter nuclei pairs, the ratio of choice for ^{10}Be decay is $^{10}\text{Be}/^9\text{Be}$, representing the relative abundance of surviving ^{10}Be to its “sister” spallation product ^9Be rather than its decay offspring ^{10}B . This alternative is afforded by the well-measured cross sections for spallation reactions in accelerators. Note that ^{10}Be is optimal for experimental purposes due to the lower mass resolution required to distinguish it from other isotopes. Of particular interest is the trans-relativistic regime of 1–10 GeV/nucleon, where time-dilation effects are sampled.

Since the mean proximity of sources from the solar system differs for the Leaky Box and halo diffusion models, the fractional abundances of radioactive nuclides expected for the two scenarios are generally disparate. Various data model comparisons were presented by Ptuskin, Soutoul & Streitmatter (OG 3.2.02), Streitmatter & Stephens (OG 3.2.03), and Simon & Molnar (OG 3.2.06), sometimes expressed as relative abundances (the experimentalists’ preference), and sometimes as surviving fractions (perhaps the theorist’s choice), which incorporate model-dependent information. Variations in theoretical predictions were modest, and preference for either the LBM or HDM is indiscernible given that model parameters can be appropriately fine-tuned; the abundance ratio data from Voyager, Ulysses and HEAO-3 missions are typically accurate to only a factor of two. Yet the potential for advances in this field in the near future is significant. The recent ACE data from the CRIS experiment (e.g. Yanasek et al. OG 1.1.03, and Weidenbeck’s highlight talk, these proceedings) reduced experimental uncertainties in these ratios in the 0.1–0.3 GeV/nucleon range down to the 20%–40% level. Further gains are anticipated with ISOMAX (Hams et al., OG 3.1.33), which will extend the range of exploration up to a few GeV, so as to more completely probe the mildly-relativistic regime.

The possible influence of galactic winds and interstellar cosmic ray re-acceleration complicate the propagation problem. Winds away from the galactic disk (typically at $\gtrsim 20$ km/sec) necessarily enhance loss rates and therefore can impose less stringent requirements on the energy dependence of the diffusion and lead to anisotropies in the diffusion tensor (Breitschwerdt, Dogiel & Völk, OG 3.2.19); these authors argue that such winds may explain the small ratio of radial gradients of diffuse gamma rays to cosmic rays. Ptuskin et al. (OG 3.2.32) indicate that wind and minimal re-acceleration models are both just as consistent with stable secondary/primary ratio data as the LBM and HDM. Re-acceleration models did not achieve the same exposure and topicality as in previous Cosmic Ray Conferences. Their basic properties are understood. Depletions of low energy cosmic rays due to *in transit* acceleration effectively eliminate the need for a broken power-law for the variation of the escape length X_{lb} with rigidity. Re-acceleration alleviates the problem of weakly rigidity-dependent, low-level anisotropies, by permitting a reduced dependence of the escape length on R . At the same time, re-acceleration has a profound influence on ions below 10 GeV/nucleon (Jones et al. OG 3.2.07) that have long residence times; this becomes an asset when trying to fit B/C and (sub-Fe)/Fe spectral flattenings in the low-energy modulation range.

In concluding the discussion of ion propagation, note that two formalism papers were contributed by Forman (OG 3.2.11) and Ragot (OG 3.2.45), which focused on quasi-linear theory aspects of particle diffusion in field turbulence (gyro-resonant and non-resonant, respectively), works that while interesting for propagation specialists, are more salient to heliospheric issues in the SH sessions.

Electrons

Considerations of electron propagation were largely confined to the work of one research group, Webber and his collaborators. Nothing extremely new was forthcoming, yet discussion of electrons provides an interesting forum for the interplay between cosmic ray physics and astrophysics. The observed cosmic ray (total) electron spectrum is steeper in the 3–100 GeV range than its ion counterpart [12], suggesting either that ions and electrons possess distinct propagation characteristics, or that electron source spectra are steeper than ion ones. This latter alternative was promoted in several papers: Stephens (OG 3.2.14), Higbie et al. (OG 3.2.15), Rockstroh et al. (OG 3.2.16) and Peterson et al. (OG 3.2.17). Inferences in this direction are facilitated by broadening the dynamic range of cosmic ray energies sampled using data of astronomical origin. The diffuse radio synchrotron spectrum is very informative since it evades modulation effects, and can therefore probe lower electron energies, principally in the 0.2–3 GeV range. However, the “model-independence” of such information is marred at low energies by significant free-free absorption in the ISM (Peterson et al. OG 3.2.17). Matching normalizations of the radio-derived e^- spectrum with the cosmic ray electron one measured at higher energies requires assuming a mean interstellar field of around $5\mu\text{G}$. While the aforementioned papers advocated an $E^{-2.4}$ electron source spectrum, the data spread is sufficient to render an $E^{-2.25}$ spectrum not implausible for the particular diffusion model invoked by Rockstroh et al and Peterson. et al. Since deductions pertaining to the cosmic ray origin are contingent upon propagation and modulation assumptions, the flatter source spectra are not presently excluded.

Higbie et al. (OG 3.2.15) argued that modelling the diffuse gamma-ray emission with the same Monte Carlo propagation simulation again points towards a steeper e^- source distribution: simultaneous fitting of the pion “decay bump” in the > 50 MeV EGRET data and the relatively steep COMPTEL 1–30 MeV spectrum with a bremsstrahlung component [13] (both experiments were on board the Compton Gamma-Ray Observatory) provides the basis for this assertion. Porter & Protheroe (OG 3.2.38) arrive at a different conclusion when modelling diffuse gamma-ray emission, arguing in favour of flatter electron source spectra. These disparate inferences largely reflect differences in propagation models, and therefore indicate the limits that should be placed on such assertions at this stage. Stephens (OG 3.2.14) addressed positron propagation and claimed a small (10–15%) charge-sign dependence of modulation; while potentially interesting, data uncertainties limit this interpretation to merely a prediction for future experimental verification.

ACCELERATION THEORY AND ASTROPHYSICS

The subject area of the theory of particle acceleration and astrophysical applications was the most diverse in terms of the material presented at the Conference. Hence, only principal focal points can be addressed in this brief exposition.

Acceleration Theory

The discussions of cosmic ray propagation hinge on the widely-used assumption that the sources of cosmic rays produce quasi-power-law populations ($E^{-\alpha}$) with $\alpha \approx 2.1-2.4$. This is readily satisfied by *test-particle* acceleration at the strong shocks formed at supernova remnant shells as the expansion ploughs through the ISM. This feature has led to the almost universal acclaim that SNRs are the site of cosmic ray acceleration, at least up to the knee at $\sim 10^{15}$ eV. Yet there are many subtleties, including those related to deviations from the test-particle approximation, how shock heating of the downstream gas is influenced by the fluid dynamics, questions of the efficiency of injection (particularly for electrons), and what are the differences between relativistic and non-relativistic shocks.

The issue of validity of the test particle approximation is important for the cosmic ray problem. The beauty of diffusive acceleration was underscored by the natural explanation it provided for the power-law slope of the cosmic ray distribution over many decades in energy. Yet this attractive feature is contingent upon two criteria: (i) that the accelerated particles do not modify the dynamics of the shocked flow, i.e. act only as test particles to the problem, and (ii) that there is no particular energy scale for losses of particles. It is palpable that neither of these properties is satisfied in shocks in SNR shells, thereby eliminating the most aesthetic reason for considering shock acceleration as the principal means of energizing cosmic rays. Nevertheless such acceleration is virtually inevitable at the interface between supersonic and subsonic flows, and hence is widely accepted to be ubiquitous in astrophysical systems by theorists and experimentalists alike.

Non-linear shock acceleration effects and their implications featured prominently in the contributed papers, and are suitably discussed in the reviews of [14,15]. When the accelerated ions have sufficient pressure to modify the flow dynamics in the shock environs, they can no longer be considered as test particles. The cosmic ray ions act to slow down the flow upstream of the shock discontinuity, resulting in an increase of the overall compression ratio r above the canonical test-particle value of $r = 4$ if the system sustains significant losses of particles or energy. This strengthening of the shock adds to the non-thermal ion pressure, modifying the flow speed further, and thereby provides a feedback that defines the non-linearity of the acceleration process. Such non-linear effects are present in SNR shocks because they are inherently strong, have had sufficient time (at least in the Sedov phase) to accumulate significant pressure in the cosmic rays, and suffer losses on the largest spatial scales. Electrons seldom contribute to the dynamics (e.g. [16]), unless they

possess a peculiarly large abundance relative to the cosmic ray e/p ratio [12] of 1–3% in the 1–10 GeV range.

A principal signature of these non-linearities in strong SNR shocks is the upward spectral curvature [17] in the non-thermal ions, a consequence of higher energy ions generally having larger diffusive scales and thereby sampling greater effective compression ratios in the cosmic ray-modified flow. Concomitantly, the acceleration is enhanced with increasing mass to charge (A/Q) ratio, implying a relative profusion of higher metallicity species that was salient for the cosmic ray origin discussion above. Berezhko & Ksenofontov (OG 3.3.09) and Ellison et al. (OG 2.2.09) illustrate such predictions of non-linear acceleration theory and emphasize that spectral curvature is consistent with all-particle or individual species data given the significant experimental spread below the knee, an argument supported by Zatsepin & Sokolskaya (OG 3.1.02). This line of reasoning is obviously at odds with the common wisdom that the cosmic ray spectrum is a beautiful power-law. Merit can be found in both perspectives, which are not inherently incompatible: the spectral curvature predicted is sufficiently small (enhancements by a factor of a few over several decades in energy) that it essentially cannot be discriminated from exact power-laws as an appropriate model for the cosmic ray spectrum below the knee. In any case, since the cosmic ray measurements represent a convolution of source properties and propagation characteristics, such a distinction loses meaning. In this regard, gamma-ray signatures in the GeV to TeV band from isolated remnants will be more informative in seeking evidence of spectral curvature.

The critical point for discussion is that spectral cutoffs expected in SNRs (generally around 10–100 TeV; see [16], Berezhko & Völk, OG 3.3.08, Yoshida & Yanagita, OG 3.3.11) could impose structure in the cosmic ray spectrum more severe than observed near the knee. This is a principal outstanding problem for cosmic ray studies; its resolution requires more detailed spectral and compositional information in the vicinity of the knee (the ACCESS project [18] should help provide this). The KASCADE air shower experiment provided some interesting results salient to this issue, namely deductions of proton and Fe spectra from muon data (Haungs et al. HE 2.2.02; Chilingarian et al. HE 2.2.04). Complementary inferences from gamma-ray upper limits (CASA-MIA results: Markoff et al. OG 3.3.18; HEGRA observations: Horns et al. OG 3.2.24) are currently not constraining.

Non-linear acceleration-induced spectral curvature obviously will impose more severe requirements on propagation models, both by requiring a stronger dependence of the escape length on rigidity and by increasing difficulties in minimizing anisotropies of the highest energy particles in the galaxy. Another non-linear feature is the reduction of the compression ratio of the viscous subshock (i.e. shock discontinuity) below $r = 4$, thereby reducing the dissipational heating of the downstream plasma (Ellison & Berezhko OG 3.3.12). This property is pertinent to the interpretation of X-ray line emission from SNRs, computations of X-ray bremsstrahlung in SNR emission models and the deduced electron-to-proton ratio [19]; the latter impacts the gamma-ray flux expected from remnants [16]. Several papers were devoted to such astrophysical signatures and are discussed below.

The injection issue was the subject of two papers, Gieseler, Jones & Kang (OG 3.3.20) and Sugiyama & Fujimoto (OG 3.3.21), though neither paper treated electron injection, a perennial concern for theorists. Gieseler et al. developed Kang & Jones' diffusion-convection equation approach to modelling acceleration at non-linear shocks by incorporating a description, due to Malkov, of the interaction of thermal ions with self-generated magneto-hydrodynamic (MHD) waves. It is unclear what advantages this step has to offer over antecedent developments by Kang & Jones that parameterized injection efficiencies (e.g. see OG 3.3.32, which discussed an interesting use of an adaptive mesh technique to improve the dynamic range of lengthscales that can be probed). The injection formalism incorporated in OG 3.3.20 is based on quasi-linear theory, which has limited applicability to turbulence in the environs of strong, modified shocks. Sugiyama & Fujimoto simulated injection in such strong turbulence by computing ion motions in large amplitude MHD waves, using techniques employed in hybrid and full plasma simulations. Their test particle investigation of essentially coherent acceleration in time-dependent electric fields in the shock neighbourhood yielded expected results, which are usually generated by more complete plasma simulations (reviewed in [15]), namely that suprathermal ions are produced in significant numbers on timescales considerably larger than the ion gyroperiod. Such coherent effects are an integral part of the dissipational heating in the shock layers, and naturally provide injection that seeds diffusive acceleration at higher energies.

From a small *pot pourri* of papers treating diverse acceleration problems, I wish to highlight two contributions before proceeding to the astrophysically-oriented offerings. The first was the presentation of a simple analytic model of non-linear acceleration in plane-parallel shocks by Ellison & Berezhko (OG 3.3.12), specifying a complete (and continuous) particle distribution via a thermal component plus a three-piece broken power-law representing non-thermal ions. The power-law slopes, energies of connection between the various spectral portions, and the normalization coefficients are self-consistently determined in a modelling of the flow hydrodynamics; only the efficiency of injection from thermal energies need be specified as a parameter. The model possesses great potential for astrophysical applications, due to its facility, and agrees well with more complete predictions of Monte Carlo [20] and kinetic transport equation [21] techniques.

The second interesting result was in the discussion by Drury et al. (OG 3.3.13, OG 3.3.16) of “pile-ups” in cosmic ray electron source distributions near the maximum (i.e. cutoff) energy due to significant synchrotron losses. This issue has had various preceding treatments, with the conclusion that only test-particle shocks with compression ratios $r > 4$ could yield a build up of electrons near the cooling cutoff, i.e. an improbable occurrence. The new feature of Drury et al.'s work is that momentum-dependent diffusion scales are treated so that synchrotron cooling of electrons sufficiently remote downstream from the shock can result in losses from the system additional to those due to convection. The criterion for build-ups relaxes to $r \gtrsim 3.5$, generating an interesting regime of phase space where strong shocks potentially can yield these spectral bumps. Essentially, pile-ups arise when mo-

momentum losses in cooling outpace the spatial losses that are integral in determining the index of the canonical test-particle distribution. Such pile-up considerations could prove very relevant to the interpretation of non-thermal X-ray emission and TeV gamma-ray spectra from SNRs.

Astrophysical Applications

Supernova remnants were the dominant subject of astrophysical applications of acceleration theory. While dynamical calculations of cosmic ray acceleration at SNR shocks and limited models of radio to gamma-ray emission from these particles have been around for a long time, this field has really burgeoned in the last half decade following the detection by the EGRET experiment on the Compton Gamma-Ray Observatory of a number of unidentified 100 MeV–10 GeV gamma-ray sources with SNR celestial associations [22] and the subsequent campaigns [23,24] by atmospheric Čerenkov telescopes to search for TeV emission from various prime candidate remnants (see [25] and Buckley’s Rapporteur paper in these proceedings for reviews of this field). The field now possesses confirmed detections in *non-thermal* X-rays and TeV gamma-rays in a few sources, an enviable position compared with the status 5 years ago. The models have rapidly become more sophisticated and complete in their radiation predictions. Two alternative techniques are at the forefront of this acceleration problem, both being represented at the Conference: (i) Berezhko et al.’s semi-analytic solution [21] of the time-dependent spherical transport equation for ions, and (ii) Ellison, Baring and collaborators’ use of a Monte Carlo simulation of diffusive acceleration [16,20]. These approaches each have their virtues and limitations. Berezhko et al.’s method handles all the time-dependent effects self-consistently, but requires a parametric specification of injection, whereas the Monte Carlo simulation, which automatically injects ions from the thermal populations, models steady-state parallel shocks and incorporates effects of time-dependence through a hybridization [16] involving Sedov evolution of shock parameters. Both methods must parameterize electron injection, an imposition due to current shortcomings in acceleration theory.

There is a remarkable convergence of results from these two complementary models, as is patently evident in the spectral comparison presented by Ellison & Berezhko (OG 3.3.27). While there are some fine-scale dissimilarities, this global agreement has led to a fairly robust set of predictions [19] for radio, X-ray and gamma-ray astronomy, embodied in the Conference papers of Berezhko and Völk (OG 3.3.08), Berezhko, Ksenofontov & Petukhov (OG 3.3.23) and Ellison et al. (OG 2.2.09). Principal features include the virtual constancy (and peaking) of the maximum particle energy and gamma-ray luminosity throughout the Sedov epoch (OG 3.3.08, OG 3.3.23), and prominent pion decay emission for high circumstellar densities in both the GeV and TeV wavebands; for ambient fields approaching 1 mG, synchrotron cooling is sufficient to render such hadronic emission dominant in the super-TeV range (Ellison et al. OG 2.2.09, and Berezhko & Völk OG 3.3.24,

who also explore remnant properties for explosions in wind bubbles spawned by massive progenitors). Such pion decay signatures are potentially almost unambiguous evidence of the presence of cosmic rays in supernova remnants. The quest for such a proof of cosmic ray acceleration in SNRs is of primal importance to the cosmic ray community. Acquisition of this evidence seems imminent, given the impending ground-based and spaced-based gamma-ray experiments scheduled to come “on-line” in the next 5–6 years. Theory is currently well-placed to interpret the anticipated wealth of new information to be afforded by these programs.

There was a marked paucity of papers addressing relativistic shocks at the Conference. This was in spite of considerable recent interest in their acceleration properties by modellers of the topical gamma-ray burst (GRB) phenomenon, and the probable relevance to generation of ultra-high energy cosmic rays. Baring (OG 2.3.03) provided the principal offering at the Conference on acceleration predictions at relativistic shocks, highlighting the major needs for GRB theorists: quantifying the injection efficiency (particularly for electrons), and determining the spectral index (which is not uniquely specified in terms of the shock compression ratio) and the time and maximum energy of acceleration. None of these properties can be discerned easily, and there is a major need to redress such gaps in our knowledge. Baring explored spectral differences between large angle scattering and pitch angle diffusion in ultrarelativistic plane-parallel shocks (i.e. those with bulk Lorentz factor $\Gamma \gg 1$), and confirmed the finding of Bednarz & Ostrowski [26] that in the case of pitch angle diffusion, the power-law spectrum for accelerated particles approaches approximately $E^{-2.2}$ as the shock speed asymptotes to the speed of light. Ostrowski (OG 3.3.07) discussed the possibility of acceleration at shear layers bordering relativistic jets in active galaxies. As intuitively expected, he observed the acceleration to be rapid due to large kinematic boosts acquired when particles diffuse between the jet and surrounding medium. Yet no indication of the efficiency of injection was proffered, and it is unclear that this type of boundary layer acceleration can be very effective in the presence of shear turbulence that is naturally established in jet entrainment of the surrounding ambient material. It is also uncertain whether such kinematic boosts to particle energies in either of these extragalactic environs can enhance the sources’ ability to generate cosmic rays with $E \gtrsim 10^{19}$ eV, an issue that should be the focus of future research.

ULTRA-HIGH ENERGY COSMIC RAYS

The study of Ultra-High Energy Cosmic Rays (UHECRs) bridges the interests of cosmic ray physicists and astrophysicists. While the perennial problem of what is the metallicity of $> 10^{19}$ eV cosmic rays (i.e. protons vs. Fe) remains, focus at this meeting was centered on the highest energy ones, namely those around and above the Greisen-Zatsepin-Kuzmin (GZK) cutoff at $\approx 5 \times 10^{19}$ eV [27,28]. This subject was driven largely by the recent announcement (Takeda et al. [29]) that there is a significant excess of cosmic rays above the GZK cutoff, with 13 events now detected

(mostly AGASA data) above 10^{20} eV. Papers at the meeting can be categorized as those discussing arrival directions and those addressing spectral issues.

Stanev and Hillas (OG 3.3.04) provided a detailed statistical analysis of arrival directions for events with energies $E > 40$ EeV, exploring possible associations and anisotropies on various angular scales. Their conclusions were that there is no significant correlation between UHECR directions and those of extragalactic supernovae, and that there was only a marginal enhancement of UHECR flux near the supergalactic plane. Ion deflections in galactic and extragalactic magnetic fields clearly de-correlate directions of prospective sources and observed events significantly. Tkaczyk (OG 3.1.14) posited upper limits to the neutron content of UHECRs via analysis of their anisotropy, using the fact that neutrons are undeflected by these magnetic fields. Stanev and Hillas did indicate, however, that there was significant clustering on angular scales less than 5° , primarily spawned by two UHECR triplets; pair groupings were not unusually numerous. The Auger [30] and Owl [31] projects will obviously increase the database dramatically, and improve such statistical analyses immeasurably. Directional information was also a focus of Horns et al. (OG 3.2.24), who used data from the HEGRA scintillation array to search for high-energy gamma-ray associations with UHECR events, and concomitant anisotropies. One particular marginal association stood out, a 4σ excess in the sky at gamma-ray energy of 10^{14} eV, coincident with the arrival direction of the 320 EeV Fly's Eye cosmic ray. In a paper supporting this directional analysis, Horns (OG 3.2.37) simulated electromagnetic cascades initiated by UHECRs.

Two discussions relating to extragalactic source spatial distributions were offered by Ptuskin, Rogovaya & Zirakashvili (OG 3.2.23) and Medina-Tanco (OG 3.2.52). These two works focused on explaining the excess implied by the UHECR observations [29], with essentially the same premise: natural clustering of galaxies provides source densities that exceed, on small distance scales, the average density for a uniform, homogeneous spatial distribution. This property obviously weights the calculation of cosmic ray cooling by photo-pion production on the microwave background, and permits a population of UHECRs above the traditional GZK cut-off at $\approx 5 \times 10^{19}$ eV. Both groups effectively assumed that cosmic ray production rates trace galaxy luminosity to some extent, since the latter underpins astronomical detectability. Ptuskin et al. and Medina-Tanco reached the same conclusion: that the galaxy distributions can permit cosmic ray distributions commensurate with the observed spectrum, thereby resolving any purported observation/theory discrepancy. Their conclusion was arrived at by different analyses: Ptuskin et al. invoked a fractal distribution of galaxies as a mathematically-motivated description of clustering, while Medina-Tanco made use of the data collection of the CfA survey at redshifts $z < 0.05$. Hence the bottom line here is that there appears to be no need to seek a galactic connection for the $> 10^{20}$ eV events.

Papers addressing the actual source of UHECRs were exceedingly sparse, with the only offerings being the galactic scenarios of Olinto, Epstein & Blasi (OG 3.3.03) and Blasi (OG 3.3.02). Olinto et al. envisage neutron stars acting as sources of ultra-high energy Fe, stripped off the stellar surfaces by intense electric

fields induced by rotation. Key properties of their picture include a very flat source spectrum, modelling structure around and above the ankle in the cosmic ray spectrum, and of course, a heavy metallicity of the UHECR population. Conditions for minimal effects of energy degradation of accelerated Fe nuclei on the surrounding pre-supernova ejecta are achieved for fast rotators, i.e. millisecond pulsars. Their model has a number of attractive features, however its viability is contingent upon the ease with which iron can be stripped from the star; this issue is somewhat controversial in the pulsar community, with skeptics (in the majority) appealing to the large work function of Fe to argue their case. Blasi (OG 3.3.02) suggested an exotic origin: super-heavy dark matter in the galactic halo, comprising postulated quasi-stable particles that are relics of the early universe. These particles are purported to spawn neutral and charged pions in spontaneous decays so that electromagnetic signatures are generated, principally gamma-rays in the > 100 MeV range appropriate for exploration by the proposed GLAST [32] experiment. This scenario suffers from the drawback that it is difficult to discriminate spectrally its predictions from those of more mainstream origins of diffuse emission. In a related paper, Medina-Tanco & Watson (OG 3.1.17) indicated that present statistical limitations on UHECR anisotropies preclude discrimination between various dark matter halo distributions. Due to the proximity of their sources, neither of these origin scenarios need to address so-called GZK-violations.

FUTURE DIRECTIONS

To conclude, it is appropriate to identify a list of salient tasks for the cosmic ray community relating to the subjects discussed here. For origin/composition specialists, the question of how old the seed material is still remains, and a reconciliation of ACE data constraints with inferences from the LiBeB problem is needed. Data on actinide abundances should help probe matter mixing timescales. It is also important to determine whether O metallicity is a better indicator than Fe/H for the LiBeB problem. For the propagation community, extending the data range of unstable secondary to primary ratios to span the trans-relativistic regime, 1–10 GeV/nucleon, will help discriminate between propagation models; while ACE has made progress here, we await future flights of ISOMAX. Improving spectra and composition studies around the knee are clearly a major priority for the acceleration community, to discern how effective SNRs are at accelerating up to these energies. A related issue is the search for pion decay signatures in gamma-ray emission from remnants, which would provide the first unequivocal proof that SNRs are indeed the galactic sites of acceleration; the opportunity for this resolution seems imminent. On the theoretical side, three-dimensional plasma simulations are desperately needed to elucidate the electron injection problem, and considerable investment in the study of acceleration at relativistic shocks would advance the astrophysics of active galaxies and gamma-ray bursts. For the UHECR field, it is anticipated that the database increase due to Auger and Owl projects will provide a clearer picture

of the spectral, anisotropy and clustering properties of such high energy particles, enabling discrimination between various postulates of their origin.

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